ARL Core Program – 1. Dispersion

Overview

Dispersion (the process of atmospheric transport and diffusion) has been a major theme behind ARL research since the inception of the laboratory in the early 1950s. The dispersion theme underpins the current ARL core capabilities related to climate variability, air quality, and air-surface exchange.

Today, it can be convincingly argued that ARL provides the dominant dispersion capability in the world. This capability is made available, in crude form, via the Internet. Vastly refined products are made available as needs arise. Note that these refined products are not made available automatically to any user, for obvious reasons related to national security. If a high quality forecast is needed, then the product needs to be arranged through contact with ARL. Such products are now routinely made available to various federal government departments.

> ARL's dispersion studies are in direct support of NOAA's Weather and Water and Homeland Security missions. In essence, the over-riding NOAA mission is to provide reliable atmospheric and marine forecasts to protect people, society, and the environment. Meteorological forecasting is probably the most important of the many NOAA products. Until recently, dispersion forecasting has been a comparatively minor part of this meteorological activity, because dispersion forecasts are rarely needed routinely or on a fixed schedule. The specialist skills have resided in OAR and in NOS rather than in NWS. Today, NWS provides dispersion forecasts through its 122 Weather Forecasting Offices. These forecasts are through the application of dispersion models developed by ARL, specifically designed to facilitate integration with the mainstream NWS weather forecasting capabilities. In the near future, these dispersion forecasts will be even more integrated with the operational NCEP systems, since the models now in final development include all of the meteorological considerations necessary to provide dispersion forecasts using information at scales that would otherwise not be feasible. In other words, the best dispersion forecasts possible will necessarily be derived from NCEP models, without any reliance on independent systems except for post-processing. ARL is actively working towards the rapid provision of such a capability.

The ARL Groups

Five ARL groups are heavily involved in dispersion research and model development.

ARL, Silver Spring concentrates on long range transport and diffusion, over ranges from regional to global and at altitudes normally above the surface boundary layer. The model development has been in association with the military. The HYSPLIT capability and all of its evaluation programs (CAPTEX, ANATEX, METREX) were all sponsored by the

DoD. The Silver Spring group works directly with the National Centers for Environmental Prediction, with which collocation is presently being planned.

ARL, Oak Ridge focuses on situations where surface conditions influence dispersion – complex terrain, patchy vegetation, coastal regions, and urban areas. The series of coastal dispersion "Model Validation Studies" of the last decade was conducted mainly under the leadership of the ARL groups at Oak Ridge and Idaho Falls. Moreover, ATDD scientists led the design of the major urban field programs of recent years – Salt Lake City, Oklahoma City and currently New York City. Their location in Oak Ridge is to ensure direct interaction with all of the DOE and NNSA activities and laboratories in Oak Ridge.

ARL, Idaho Falls is the national center of excellence for conducting atmospheric tracer studies. Their scientists have developed gaseous tracers and the methods for detecting them in trace quantities, and have a long history of developing and using instrumented balloons of many different configurations. The group is located at Idaho Falls to provide independent dispersion guidance to the Idaho National Energy and Environmental Laboratory.

The **ARL Las Vegas** group serves as the linkage with a major client for ARL dispersion research – the Department of Energy. The Special Operations and Research Division of ARL is the group that transfers the ARL dispersion products into an operational environment on an interactive and developmental basis. This group is located at Las Vegas to provide independent guidance to the Nevada Test Site and all of its weapons development programs (and other national security activities). ARL serves as the leader of the DOE Meteorological Coordinating Council, which provides meteorological guidance to all DOE facilities.

ARL, Research Triangle Park is the group that serves in a parallel way with the EPA. This group transfers dispersion products to the air quality community, through the processes available to the air quality assessment and regulatory community. The location at Research Triangle Park is to ensure interaction with the EPA research group located there.

Some History

Concerns about dispersion have plagued civilization for centuries. An early but notable example was the deployment of simple sulfur dioxide sensors across southern France, to find the origin of the pollution that was affecting the French silk industry. The plume that was mapped pointed to London, and one of the first international air quality negotiations then followed. The head of the French National Academy at the time was Louis Pasteur. This was a case in which the dispersion of relevance took place in the lower atmosphere. Understanding about dispersion on a global scale, in the upper atmosphere, took a leap forward with the studies of the spread of ash from the eruption of Krakatoa, in the early 1800s. The global spread of the resulting ash cloud was monitored carefully, with results reported in a beautifully illustrated volume published by the British Royal Society.

In more modern times, it was gas warfare in World War I that alerted the scientific community to the need to understand more about what controlled dispersion near the ground. The work expanded during World War II, with strong alliances being generated among dispersion scientists in England, Canada, Australia, and the USA.

With the arrival of peace in 1945, the gas warfare studies slowed greatly. However, the need to test nuclear weapons made studies of the spread of radioactive fallout a critical component of the national security research infrastructure. Radioactive fallout was easy to measure, and understanding of the mechanisms that caused it to spread around the world expanded rapidly (largely as a direct consequence of research programs conducted by ARL). In this case, there were several very practical purposes for the research that was initiated. First, there was continuing worry that the fallout from tests would cause widespread damage, either to public health, climate, the environment, or the perception of the value of the testing program. The National Weather Service was called in to work with the military on the forecasting and assessment of radioactive fallout. Before long, these same skills were being used to help find out how, when and where Russian tests were being conducted. Again, it was the Weather Bureau that led the way, through its Special Projects Office. This office later became the Air Resources Laboratories, and later still the current Air Resources Laboratory of NOAA.

Today, ARL remains the center of excellence for dispersion in NOAA. With the emergence of Homeland Security as a major national concern, ARL capabilities have become exceedingly popular and in great demand. A big problem is that other agencies see the provision of dispersion forecasts and related expertise as an integral component of the main NOAA mission related to meteorological forecasting, and hence assume that all related activities within NOAA are financially supported by NOAA. In practice, dispersion research in NOAA has historically been supported by other agencies. This has proved an obstacle to improving relationships among the various agencies. In practice, ARL studies and developments related to dispersion have concentrated on issues of air pollution and national security. "Homeland Security" is seen as a subset of this larger program.

International transport

The distance over which a pollutant is dispersed depends on its residence time in the air, itself a function of the chemical's reactivity, solubility, and surface capture characteristics. Independently, the distance is influenced strongly by the altitude of effective injection – the higher the height of injection, the greater the distance of transport and dispersion.

Tracking the path of radioactive fallout required an emphasis on transport at altitudes higher than those of standard weather forecasting, and related uncertainties were soon encountered. ARL initiated and conducted a major study of transport across the Pacific, using then newly-developed constant-level balloons to monitor transport patterns from Asia to the USA and beyond. The results were used to refine trajectory models that were then in their infancy.

Most of the phenomena of relevance were stratospheric. ARL scientists designed and led much of the global sampling program conducted by the Atomic Energy Commission in the 1960s, involving the use of U-2 and later WB-57F aircraft and “HiBall” balloons, flying from bases in the USA and in Australia.

It was this sampling program that permitted the first studies of volcanic ash at stratospheric levels – following the eruption of Mount Agung, on Bali in Indonesia.

The development of tracers

Small-scale field studies in which tracers were released into the air became frequent in the 1960s and 1970s. ARL’s Field Research Division in Idaho Falls was a leader of such studies (a role that continues to this day), many of which were conducted under sponsorship of the military. Some of the tracer materials were particulate – zinc sulfide powder was used in many studies, pollen in others. Today, particulate tracer possibilities have been expanded greatly with the demonstrated capability to measure very low concentrations of rare earths such as ytterbium. The development of electron capture ion chromatography by Jim Lovelock (then working with the Air Resources Laboratory at its Idaho Falls office, and later the originator of the popular “Gaia Hypothesis.”) was the single step that has resulted in modern atmospheric tracer studies. This measurement methodology permits a special class of unusual molecules to be measured with precision at very low concentrations. Sulfur hexafluoride is a member of this class of molecules. (Refrigerants are also well measured in this way. Lovelock’s methods form the basis for much of the work on fluorocarbons in the atmosphere and their relationship with the “ozone hole.”) SF_6 is a chemical commonly used as an insulator in high voltage transformers at electrical substations, and so is readily available commercially. To this day, SF_6 remains the tracer gas of choice for most atmospheric dispersion experiments. However, the ability to detect SF_6 and the background level that results from its widespread industrial use mean that its use is limited to ranges no larger than one or maybe two hundred kilometers.

Concerns about the spread of radioactivity were underlined when Reactor #2 at Three Mile Island suffered a meltdown. ARL’s dispersion experts were among the first on the scene. It quickly became clear that the nation’s various plume dispersion capabilities were producing inconsistent results. What was needed was more field studies, but this time over the distances of concern to the radioactive fallout community. Chemical sensing technologies again came to the rescue, yielding systems that are capable of detecting fluoridated hydrocarbons (perfluorocarbons -- PFCs) at exceedingly low concentrations. The chemicals in question are derivatives of the refrigerants in common use, in which a chlorine atom is replaced by fluorine.

The military community was in special need of dispersion models suitable for guiding sniffers to areas where samples from Soviet nuclear tests could be collected as soon as possible after the test occurred. To augment the long range transport studies across the Pacific, a series of tracer studies was initiated, conducted by the Air Resources Laboratory under sponsorship of the military. The Cross Appalachian Experiment (CAPTEX) was conducted in 1983, to test the applicability of models to describe dispersion interrupted by a mountain range. The Across North America Transport Experiment (ANATEX) was conducted in 1987, to test models over considerable longer distances. The ARL HYSPLIT dispersion model evolved from these studies.

Urban Dispersion

The special complexities associated with cities and urban areas are obvious. To generate a data set on which urban dispersion models could be based, a year-long dispersion study was conducted in Washington, DC, in 1984. This study employed three different PFCs, released at different locations around the Washington beltway. This was the well-known ARL METREX study. In essence, METREX makes Washington, DC, the most thoroughly studied urban area in the world, from the viewpoint of dispersion. It is for this reason that Washington has been identified as the center of attention for the now evolving urban atmospheric research program, a joint activity of ARL and EPA.

> (Note that only work conducted in unclassified or declassified programs is addressed here. There is a large inventory of additional work.)

In an urban situation, there is need to consider the role of the canopy – the array of surface structures (trees, buildings) that defines the movement of air near the surface, often independently of air motions above this canopy. It is common to differentiate between "skimming flow" that moves air across the canopy, driven by mesoscale meteorology, and sub-canopy flow. The ways in which these interact and how air and pollutants are transferred between them remains a major topic for research.

ARL was a major contributor to the recent urban dispersion studies in Salt Lake City and Oklahoma City. These studies were funded by the Departments of Defense, Energy, and Homeland Security. It is often overlooked that, although the funding was from other agencies, much of the actual work was done by ARL scientists from Idaho Falls and from Oak Ridge.

Recently, some ARL work has focused on the way in which tracers "of opportunity" can be employed. The intent is to provide a round-the-clock understanding of behavior in cities. This is in direct contrast to work by the Department of Defense, which is oriented towards improving understanding so as to yield accurate forecasts in the absence of on-scene data. However, the continental USA is data rich. Just as the challenge has been for the military to learn how to predict the important meteorological drivers in demanding circumstance, the parallel civilian focus might well have been on how to extract the relevant data from the multitude of data sources that are available. Unfortunately, the former approach has dominated the dispersion research community. It is only in the post

9/11 era that the second focus has started to generate some momentum.   ARL has emerged as a national leader.

It should be emphasized that the ability to forecast wind speed and direction across an urban area is quite deficient, although good results can be obtained on the average. Unfortunately, it is not average situations that are the current goal. Rather, the need is to forecast for the specific situation in which a release actually occurs.

> In other words, the often-heard claim that models can successfully forecast wind speed and direction across an urban area might well be valid on the average, but is most certainly wrong on an event basis.

In practice, knowledge of the locality in which an event occurs is critical. We must avoid the temptation to accept forecasts provided by some central authority and distributed without quality control (or a "sanity check") by local meteorologists. To this end, NOAA provides its dispersion forecasts through its 122 Weather Forecast Offices, each of which is intimately connected with local emergency response personnel.

The Regional Specialized Meteorological Centers.

The Chernobyl accident triggered a response from dispersion modelers, worldwide. Managers of the accident were deluged with dispersion forecasts generated by a large community of scientists, each fervently believing in the unique advantages of the product being advocated. At that time, the World Meteorological Organization stepped in, and sought an official provider of dispersion forecasts in the event of a dispersion episode crossing international boundaries. The French product was initially identified. The British then volunteered to join the international community, and a start was made on a small network of Regional Specialized Meteorological Centers that now has expanded to include Russia, Japan, China, Australia, Canada, and the USA. The USA product is provided as a joint venture of the National Centers for Environmental Prediction (NCEP) of the National Weather Service and NOAA/ARL. The product is essentially HYSPLIT, driven by whatever meteorological forecast system might be deemed appropriate. HYSPLIT also constitutes the core of the RSMC product lines in China and Australia.

The RSMC community represents a global network of collaborating dispersion scientists. Canada serves as a back-up for the USA and *vice versa*. Once every month, a comparison study is conducted, involving the US, Canada, and Australian RSMCs.   At this time, there is a formal agreement with the International Atomic Energy Agency under which responsibility for generating dispersion forecasts in the event of a nuclear event is with the RSMCs. A similar collaboration exists with the Comprehensive Test Ban Treaty (CBTB) Office in Vienna. ARL's HYSPLIT is one of the models used in the CBTB process.

There are parallel activities within the international military community, in which US leadership and participation tends to be through either DTRA or Navy. In most such cases, there is interaction between the military and the ARL activity.

National Security programs

The ARL groups at Silver Spring, Oak Ridge, Las Vegas and Idaho Falls all benefit from extensive involvement in national security programs. Many of these programs result in understanding and in data sets that are then classified. Hence, no open-literature reports are produced. However, the scientific understanding that results can be used to refine civilian products, such as those delivered to the NWS by ARL. There is often doubt expressed about how it is known that these products work well. Unfortunately, answers cannot always be given.

The ARL group at Idaho Falls is especially affected by the controls imposed on release of results from field and other studies. This group's long history of productive leadership of dispersion studies is well known in military circles, but is not well recognized elsewhere because the products cannot be published.

Similar constraints apply in the case of the Las Vegas group. However, the situation at both Idaho Falls and at Las Vegas suffers from an additional constraint that is of critical importance. At both Idaho Falls and Las Vegas, studies are conducted that involve radioactivity and other potentially hazardous materials, some of which risk release into the atmosphere. A key role of the ARL dispersion experts is to provide independent guidance to the program leadership. As an example of the importance of the ARL contribution to these national security programs, note that in past years the final permission to conduct a test of a nuclear weapon was based on dispersion forecasts provided by ARL. In both Idaho Falls and Las Vegas, the research programs have been constructed to build upon the expertise required to provide the safety guidance required by the national security programs there.

The Department of Homeland Security and other US organizations involved.

In the beginning, military aspects of the dispersion problem were handled within the military. In the civilian sector, work was confined to the Weather Bureau. Within the Weather Bureau, it was the Special Projects Branch that led the way. Today, the Special Projects Branch has evolved into the Air Resources Laboratory, which continues to provide expert input to the National Weather Service (and to various other agencies).

The Weather Bureau consciously elected to provide generic information, not tailored to satisfy the mission requirements of special clients. Hence, different agencies generated specialized capabilities to answer questions related to their own particular requirements. Several of the National Laboratories requested support from the Special Projects Branch – such as the Oak Ridge and Brookhaven National Laboratories. Most national laboratories decided to generate their own systems to couple with their own emergency requirements. The leaders in this national laboratory dispersion community were Savannah River, Lawrence Livermore, Los Alamos, and Argonne National Laboratories. Brookhaven eventually decided to work independently of the Weather Bureau connection. The Department of Energy's Dispersion Modeling Coordination Committee was set up in the early years of the growing DOE program, to provide a forum for discussion among the various national laboratory scientists. The DMCC is chaired by NOAA/ARL.

It was the Oak Ridge component of the Weather Bureau's Special Projects Branch that generated the Gaussian Plume approximation to dispersion. Widespread acceptance of the Gaussian formulation led to a number of developments, including various forms of puff and segmented plume models, all based on the Gaussian assumption. These developments invariably involved ARL scientists, from one of the several ARL groups working on the problem. In addition, the generally-accepted plume rise model was developed by ARL.

> For many years, development of a specialized dispersion model was a popular topic for post-graduate thesis work. Upon completion of the university program, successful doctorate candidates would carry their accomplishment to the agency with which they gained employment, whereupon the model in question would become the preferred tool of that agency. This simple process has led to the present large number of models. There are some hundreds in current use, all tailored to some specific requirement. A recent review by the Office of the Federal Coordinator for Meteorology has revealed, however, that only seven are fully operational, nationwide. Two of these are ARL systems.

Today, the Department of Homeland Security is a major player. However, there is great awareness that DHS should not replicate the capabilities of other agencies. DHS sees NOAA as the source of meteorological information, and as one of the providers of dispersion forecasts. Under a Memorandum of Understanding now in final stages of development, ARL's HYSPLIT products will be among the few delivered to DHS for their use in providing guidance to the Secretary of Homeland Security in the event of a national emergency. ARL remains the sources of dispersion products for the NWS, for distribution through its 122 Weather Forecast Offices in response to dispersion requests from first responders and from other local authorities.

Salt Lake City, Oklahoma City, and New York City

As mentioned above, ARL scientists from Idaho Falls and Oak Ridge helped design and conduct much of the research involved in the recent well-known dispersion studies of Salt Lake City and Oklahoma City. ARL's Idaho Falls group conducted the tracer studies, releasing small quantities of trace gas and deploying highly sensitive sensing systems to detect the plume downwind. Meteorological instrumentation at Oklahoma City was provided by ARL's Oak Ridge group, which also served as one of the leaders of the overall scientific program. ARL's role in leading much of the science resulted in an expanded role for NOAA. In addition to the mainstream roles mentioned above, the NOAA Twin Otter supported by ARL took part in the Oklahoma City study, measuring turbulence and air-surface exchange across the urban area to provide surface flux data for use in the new-generation models that were being evaluated. In addition, arrangements were made for involvement of scientists from NSSL and from the University of Oklahoma, thus further expanding the level of NOAA involvement.

The team that successfully conducted the Oklahoma City study has been reconstituted for the study of dispersion in New York City that is now starting. It is anticipated that ARL will be a leading contributor to the design of the study and will conduct the SF_6 tracer studies. In addition, ARL Research Triangle Park will study dispersion across mid-town Manhattan using wind tunnel modeling and computational fluid dynamics modeling. At this time, ARL is actively working with the NWS and Brookhaven National Laboratory to expand meteorological data coverage of the target area.

Washington, DC, and Las Vegas

Immediately following the World Trade Center attack on 11 September 2001, discussions started among the agencies with dispersion credentials about the need to provide dispersion forecasts for major metropolitan areas. Washington, DC, was seen to be a major concern. At that time, the Department of Homeland Security did not exist. Guidance was provided directly from OSTP and the White House. On the basis of these discussions, ARL deployed a number of advanced meteorological stations at strategic locations across the downtown Washington area, and eventually extending to Silver Spring. The plan was to arrange for systems to make use of the observations, in real time, and for these systems to adjust dispersion forecasts based on the latest fine-grid forecasts using the specialized observations. In the following years, the tower array has grown and two systems have been developed to make use of the data derived. One of these systems is the self-standing system originally contemplated. Systems of this kind are now in place at a number of locations, including the DC Emergency Management Office and the DOC Emergency Operations Center. The second system is a development of the operational dispersion forecasting system already in place at NCEP.

Two of the towers designed for deployment in the Washington, DC, “DCNet” have been deployed at New York City, in support of the DHS dispersion study soon to start there.

All data from these systems are made available to legitimate end users in real time, and to researchers with a time delay (to prohibit misuse of the data). Identification of who has access to which data is through direct discussion with the NOAA Homeland Security Office.

In the past several months, extensive discussions have taken place in Las Vegas, concerning the need for a similar program there. Agreements have been reached among a number of local, state and federal agencies that will lead to a system like DCNet soon becoming quasi-operational in Las Vegas. The main thrust will be directed towards air quality issues in general. The urban network to be set up will be an extension of the ARL mesonet already running in southern Nevada.

> Special systems specifically requested by the White House were developed by ARL and are now key elements of the operation of the Homeland Security

Operations Center (HSOC), the clearing house for all emergency operations in the USA. These systems are in continuing development by ARL.

Volcanic Ash

Ash plumes from volcanoes represent a major hazard to aircraft. The ash can deposit on the compressor blades of jet engines, causing imbalance and shutdown. ARL has developed methodologies for predicting the plume of ash downwind of an erupting volcano, and with the collaboration of NCEP has developed a system for disseminating the guidance to airlines and other interested parties. Internationally, the overall operation is referred to as the network of Volcanic Ash Advisory Centers, set up under the auspices of the International Civil Aviation Organization and the World Meteorological Organization.

At this time, the systems that have been operational at NCEP are being refined, by installing HYSPLIT as the operational model to replace the earlier model – VAFTAD. The matter is of current importance because of fears that Mt. St. Helens could erupt.

ARL Core Program – 2. Air Quality

Overview

For forty years, ARL has served as a focus for the nation's research on air quality. The activity started in the 1960s with the recognition that the then emerging air quality concerns of the nation required attention using numerical models. A collaborative program was set up between the Public Health Service and ESSA's Air Resources Laboratories, which remains the centerpiece of ARL's air quality research to this day.

> At this time, ARL research on air quality is aimed directly at improving the ability to assess and to forecast changes in air quality due to changes in emissions, meteorology, and climate. ARL products have been operationalized within both EPA and NOAA, as well as in most States and in a number of foreign jurisdictions. All of this ARL work is directly associated with the NOAA Weather and Water mission goal, with parallel association with both Climate and Ecosystem activities.

The dispersion processes that dominated much of ARL's research during its early years were soon recognized as being the factors that controlled much of the air quality regimes downwind of pollution sources. There was, at that time, an independent specialty addressing air chemistry. Air quality was seen as a combination of air chemistry and meteorology.

The meteorology of relevance was primarily that of the lower atmosphere. In the early days of air quality studies, meteorological models were largely inadequate, because they focused on the parts of the atmosphere where synoptic changes occurred, and lacked the fine attention to the surface layer that air quality considerations demanded. For many years, the air quality community, led by ARL, led the move to develop mesoscale meteorological models. It is now not well acknowledged that the development of the MM-series of models at Pennsylvania State University was initially funded by ARL, as a step towards improving air quality simulations.

The acid rain debate of the 1980s focused attention on the major ions – sulfur and nitrogen compounds. In parallel with this, work on ozone expanded greatly. Research on the meteorology affecting air quality was conducted at Oak Ridge and Silver Spring. The development of related models (Lagrangian as well as Eulerian) took place at both of these locations, but eventually became dominated by developments at Research Triangle Park using fully Eulerian assessment capabilities in which many alternative descriptions of air chemical processes were available. These developments initially led to the Regional Acid Deposition Model (RADM) and have now culminated in the Community Multiscale Air Quality (CMAQ) model. These models are the foundations of the national air quality regulatory process. CMAQ is now the basis for the new NOAA air quality forecasting system.

ARL is a research laboratory, with a superb track record for transferring research products into operations. The development of RADM and CMAQ constitutes an operationalization of the research conducted by ARL and under ARL sponsorship during the 1980s and 1990s. Ozone is a major pollutant addressed in CMAQ; it was not addressed in RADM. The transfer to operations of ARL air quality research (both meteorological and air chemical) during the 1980s and 1990s has taken about a decade to accomplish. Today, the related focus is on refining the models for major ions and ozone, and on extending understanding so that pollutants of special interest (such as mercury, persistent organic pollutants, and the consequences of forest fires) can be addressed.

Today, air quality forecasting is a matter of urgent and immediate interest by the National Weather Service and by its partners in the EPA. The ARL capabilities, developed over forty years of continuing research, are central in the NWS system that was recently operationalized. The reliance on the ARL "CMAQ" product means that the same basic model is now being used for the nation's regulatory as well as forecasting needs.

The ARL Groups

Five ARL groups are heavily involved in air quality research and model development.

ARL, Silver Spring concentrates on hybrid approaches to air quality modeling, with HYSPLIT-chem as the flagship and with a recent focus on forest fires. The first ARL air quality forecasts were made available in the early 1990s, for areas of Texas and using reduced form chemical methods that had proved successful elsewhere. Today, HYSPLIT-chem incorporates a fully expanded Eulerian chemistry capability, coupled with the operational hybrid dispersion scheme.

ARL, Oak Ridge focuses on situations where topography and other surface conditions influence air quality. The East Tennessee Ozone Study (ETOS) has grown into a major program, following widespread recognition that air quality in the Great Smoky Mountains National Park is rapidly deteriorating, along with air quality in eastern Tennessee in general. The dominating issue is the extent to which long range transport at high elevations influences ozone concentrations affecting tourism in the Great Smokies. It is proposed to integrate information from ETOS into the air quality forecasting program.

ARL, Las Vegas will be a major player in the Urban Atmospheric Research program now being initiated with the Cooperative Institute for Atmospheric Sciences and Terrestrial Applications and a number of federal and state agencies. The study will center on Las Vegas. As a first step, ARL will instrument a number of locations with ozone monitors to demonstrate the importance of inflow of ozone and ozone precursors into the Las Vegas valley. All ARL groups are involved.

ARL, Research Triangle Park is the main ARL group addressing air quality issues. In the past, the effort has been directed towards needs of policy and assessment. Today, this historic effort is paralleled by a joint EPA/NOAA program to institutionalize air quality forecasting. ARL/RTP leads in the generation of emissions inventories, both natural and anthropogenic. The recent air quality models developed at RTP are genuine community products – they are frameworks which a user can configure to employ a variety of specialized modules. Today, these models are being refined to address a wide range of air pollutants other than the conventional species (SOx, NOx, and O_3). Airborne particles are a major target for development. In addition, the air quality models are being coupled with models of transport and chemistry in other media, so that a new generation of multi-media capabilities is being developed.

Work at RTP has extended to physical modeling, and is currently focusing on urban issues.

ARL, Boulder, operates the national surface radiation networks, which have been arranged to yield routine data on aerosol loadings of the lower atmosphere. This is in anticipation of a growing need for high quality observations to help develop and eventually to evaluate air quality particle (PM 2.5) forecasts.

Some History

The ARL development of dispersion models led to a rapid extension to address air quality issues, initially associated with emissions from specific point sources. The Public Health Service and ESSA entered into an agreement that predated the more formal partnership of later years, forming a collaborative endeavor at Cincinnati, later to be relocated to Research Triangle Park, North Carolina. The goal was to develop and operationalize models for assessing air quality and for developing related policy and regulations.

With the foundation of EPA and NOAA, the existing agreements were extended to make use of NOAA science to support the meteorological and air quality needs of the EPA. The group at Research Triangle Park became one of the Air Resources Laboratories, and later a Division of the Air Resources Laboratory.

At the same time, the air quality aspects of dispersion were increasingly recognized to have high-altitude ramifications and global-scale relevance. The global monitoring components of ARL evolved during his period and grew into the program now constituting the Climate Monitoring and Diagnostics Laboratory. Analysis of the air chemistry data obtained was historically by the ARL teams at Silver Spring and Oak Ridge. After the separation of CMDL from ARL, these extra-Boulder activities served as the foundation of a continuing ARL climate and global air quality program. This will be addressed separately.

International Aspects

ARL provides the NOAA linkage with many international programs addressing various aspects of air quality. For example . . . .

- ARL works closely with WMO's Global Atmosphere Watch

- NATO air quality activities are under ARL leadership
- ARL participates as a member of the Air Quality Board of the International Joint Commission
- ARL participates in discussions with Canada under the Air Quality Accords
- ARL provides one of the joint chairmen of the North American Agreement on Environmental Cooperation effort to rationalize monitoring across North America
- ARL provide US input to international discussions of mercury in the environment
- ARL provided the forest fire forecasting capability now used in southeast Asia (centered in Singapore but servicing Indonesia, Malaysia, Brunei, etc.).

Forest Fire Plume Chemistry

ARL is strongly linked with USFS, NASA, EPA, NESDIS and NWS in the development of forest fire plume products. There are two different products required – one that concentrates on smoke and visibility, and the other that focuses on the downwind air chemical consequences of the emissions from the fires. Currently, ARL is also using both NASA and NESDIS satellite products to map the temporal and spatial location of major fires over large regional or continental domains. Using this information, emission models such as the USFS Blue Sky system can be applied to estimate smoke emissions. ARL is adjusting the HYSPLIT-chem model to accept the source term information yielded by an alternative USFS module (RTFEI), and to simulate the way in which the chemical plume(s) interact with the background atmosphere. The intent is to provide guidance to managers who fear causing downwind areas to experience ozone (and particle) exceedances due to the fires that are under their control.

Recent interest by the NWS has resulted in the transfer of the already-existing Blue Sky wildfire emission algorithm (from Seattle) to ARL to incorporate into the current NESDIS demonstration system for a crude PM2.5 estimate. NWS is also supporting the development of a wildfire emission algorithm for CMAQ, at Research Triangle Park. In the end, it is anticipated that the Missoula emissions algorithm (see above) will also be used, after testing in the context of HYSPLIT. All of this activity builds upon the southeast Asia activity led by ARL in response to the Indonesian fires of the past decade.

A fully Eulerian product is being developed at Research Triangle Park, resulting from interactions between USFS and EPA. The guiding purpose of this development will be the assessment of potential risk related to the needs of planning and management within USFS and EPA. At this time, initial steps are being taken to facilitate the integration of this effort with the NOAA programmatic needs for related air quality forecasting. This system will make use of a source term algorithm independently developed from the USFS/NOAA process outlined above and other USFS/EPA interactions.

Urban Air Quality

The need to provide forecasts to people where people need the forecasts is well recognized. The new Urban Atmospheric Research program of ARL is designed to combine the various aspects of the problem – dispersion, air quality, and weather forecasting.

Following initial work in Washington, DC, the ARL focus now anticipated will be on Las Vegas, where there is an urgent need to understand the reasons for local ozone exceedances. The Las Vegas study will build upon the existence of the ARL mesonet in southern Nevada, which will be extended into the Las Vegas urban area.

At the present time, plans are being made to deploy a number of air quality monitors upwind of Las Vegas and at some locations within the Las Vegas valley, to provide data for use in conjunction with the fine-grid modeling activity already under way by ARL and CIASTA. The intent is to provide direct evidence of the relative role of long range transport in determining local air quality.

The Western Atlantic Ocean Experiment (WATOX)

WATOX was a series of ARL-led studies conducted off the east coast of the USA during the acid rain era of the 1980s, to assess the transport of atmospheric pollution from the continental USA across the Atlantic Ocean. The studies included extensive aircraft measurements of sulfur and nitrogen species, and of ozone, supported by surface measurements at a variety of locations (e.g. Bermuda). The studies revealed that advection can transport large quantities of pollution from North America to Europe, but that the behavior is controlled by meteorological factors and is strongly seasonal. In winter, convection over the Gulf Stream can lift pollution into the free troposphere, facilitating transport to Europe. Cold fronts can also lift pollutants into the free troposphere (in this case with elevated ozone concentrations resulting form stratospheric incursion via folds in the tropopause). In summer, convection over the continent can be the key mechanism by which pollution is entrained in the free troposphere, again facilitating long range transport.

In the 1960s, ARL conducted a program focusing on intercontinental transport, in which series of constant-level balloons were released into the upper troposphere and tracked over distances typically exceeding 5000 km. Work on balloon technology has continued, with the recent development of “smart balloons” that can be used to address issues of transport at lower elevations.

Precipitation Chemistry and the Global Precipitation Chemistry Program (GPCP)

Trends in air quality are difficult to detect, largely because of the large variability air concentrations. In practice, the need to maintain sensitive instruments so that they can detect small differences with confidence compounds the difficulties. For many years, ARL has promoted the use of precipitation chemistry as an indicator of air chemistry. For the major ions (sulfur and nitrogen species) and for a variety of other pollutants, precipitation chemistry is easier to measure than air chemistry. During the 1980s and early 1990s, ARL and the University of Virginia conducted an extensive program to describe precipitation chemistry regimes at a range of remote locations, distributed globally. This work was in close association with the Global Atmosphere Watch of the World Meteorological Organization.

The program continues to receive attention, because of the recognition that revisiting these GPCP sites could reveal changes occurring over the intervening years. Information regarding trends in air quality at remote locations is sorely needed, and precipitation chemistry is a useful surrogate.

The Bay Regional Air Chemistry Experiment (BRACE)

The ARL aircraft, turbulence, air chemistry and modeling capabilities were extensively exercised in the BRACE study 2001-2003, centered on Tampa Bay. BRACE was conducted in collaboration with the Florida Department of Environmental Protection and the EPA. The goal was to explore the mechanisms by which nitrogen species) especially including ammonia) entered Tampa Bay, and to identify the sources of these inputs.

One of the NOAA Twin Otter aircraft was equipped to measure tropospheric eddy fluxes and concentration gradients, from which direct measurements of air-surface exchange rates of various trace gases can be derived. Fast response measurements of tempeerature, water vapor, carbon dioxide; and supporting measurements of dew point, pressure, 3-D winds, and solar radiation were obtained. ARL systems were used to measure NO, NOx, NOy, SO_2, O_3, CO, and reactive hydrocarbons. Flights were made to characterize transport and transformation of air pollutants in the urban plume.

In parallel with this work, an ARL-developed chemical transformation and dispersion model was used to simulate the situation, using a 2-km grid and hence permitting detailed consideration of the effects of land-sea breezes, the in-air production of aerosols, and the deposition of gases and aerosols, including ammonia. At this time, analysis of the data obtained is nearing completion.

Mercury in Air

Concerns about the bioaccumulation of mercury in fish and marine mammals started during the mid 1990s, and ARL scientists quickly became involved. The major sources of the mercury are now well known to be the burning of coal for electric power generation, various forms of incineration, and a multitude of other activities. The mercury enters the air mainly as gaseous elemental mercury and as reactive gaseous compounds of mercury. Elemental mercury has a very long residence time in the atmosphere; it does not deposit quickly. However, the reactive species do deposit rapidly and give rise to deposition “hot-spots” downwind of emission sources. The question that needs to be answered relates to the role of long-range transport of elemental mercury followed by transformation to reactive chemical species, versus deposition of the reactive species that are directly emitted. Once deposited, the mercury is affected by biological activity and enters the food chain, where it eventually accumulates in the tissues of fish (e.g.) that can then be consumed by people. It is the adverse consequences of bioaccumulation of mercury that drive concerns about this particular pollutant.

A series of aircraft measurements was conducted in 2000, over the Florida coast where the question of local versus distant sources is politically charged. ARL scientists from Silver Spring, Research Triangle Park, Oak Ridge, and Idaho Falls were involved.
In collaboration with EPA and Oak Ridge National Laboratory, a study of mercury behavior at high latitudes was then initiated. (At high latitudes there is known to be a major burst of mercury deposition every spring, for reasons that were not initially known.) The ARL studies indicated that there is a significant role of halogens (thought to be dominated by bromine) in the reactions by which atmospheric elemental mercury is transformed into RGM. This has subsequently been supported by studies conducted in Antarctica, again by ARL scientists.

There are two modeling efforts currently under way – one fully Eulerian and the other quasi-Lagrangian. These two efforts are primarily intended to satisfy the needs of two different communities, the first being the policy and assessment community, and the second the community identifying where best to focus emission controls in order to minimize deposition. Both activities are internationally recognized. In essence, the two groups involved (Research Triangle Park and Silver Spring) dominate the US mercury modeling scene.

At this time, ARL is leading NOAA efforts to generate a multi-line office program to address mercury in the environment, from sources to eventual intake by people. This program features prominently in NOAA plans for ecosystem research.

ARL Core Program – 3. Air Surface Exchange

Overview

The energy that drives the atmosphere comes from the sun. This heat is transferred to the atmosphere through a variety of processes that are categorized as "air-surface exchange." The dominant process is convection, occurring during daytime. This convective exchange also transfers water vapor, carbon dioxide, and a variety of trace gas and particulate pollutants. Weather forecasting models require accurate depictions of the heat energy that drives the atmosphere (and of the surface friction that controls winds). Hydrological models require accurate depictions of water exchange. Climate models need descriptions of the surface exchange rates of a wide range of quantities. It is ARL science that underpins national measurement programs addressing these requirements, through developing new measurement methods and new formulations for the exchange processes. Air-surface exchange is central to weather, climate, and air quality prediction. The NOAA goal to improve its forecasting capabilities, in all aspects, carries with it a need to study, understand and parameterize air surface exchange of all atmospheric properties, from momentum to pollutants.

> This ARL core capability supports several NOAA goals, specifically those related to the development of an ecosystem approach to management, to improving the forecasting of weather, and to refine the ability to understand and predict changes in climate.

Measurement and modeling of air-surface exchange has been a mainstream activity of ARL for more than 25 years. The exchange of pollutants associated with precipitation has been a specialty that originated in the early days of the laboratory, when the goals related to radioactive fallout. Dry deposition studies originated in the same era. Work on the processes that control exchange started with a focus on the standard meteorological quantities – heat, moisture and momentum, but quickly evolved into studies of trace gas and particle exchange.

The role of ARL has been to improve measurement technology and understanding. Many of the ARL developments are now mainstream in the meteorological community, and ARL research has accordingly moved forward. For example, the eddy correlation tower measurement of heat, moisture and momentum is now easily accomplished using off-the-shelf instrumentation. Much of this technology was developed by ARL, but today ARL scientists are progressing even further, leaving the routine measurement of such quantities to others. At this time, the focus of ARL air-surface exchange studies is on complex terrain, aircraft systems, trace gas exchange (emission and deposition) and particle exchange (again, emission and deposition). All ARL groups are involved.

Dry deposition and wet deposition monitoring are subsets of the overall program. In both instances, the ARL focus is to provide the research and development activity necessary to underpin the national routine monitoring efforts, given that all routine measurements programs of this kind are imperfect (e.g. they do not address spatial averages, and are of questionable relevance in complex terrain). These national programs are the multi-agency National Atmospheric Deposition Program (NADP, for wet deposition) and the Clean Air Status and Trends Network (CASTNet, for dry deposition). The ARL Atmospheric Integrated Research Monitoring Network (AIRMoN) is the research and development program that supports these routine national monitoring networks.

The ARL Groups Involved

Five ARL groups participate in the AIR air-surface exchange program.

ARL, Silver Spring concentrates on the exchange of pollutants in precipitation. This work is strongly coupled with the National Atmospheric Deposition Program (NADP) and in closely associated with related international programs under the auspices of the World Meteorological Organization's Global Atmosphere Watch. ARL leads the international effort to integrate global efforts to monitor precipitation and aerosol chemistry, under the auspices of the GAW. AIRMoN-wet is led by ARL Silver Spring.

ARL, Oak Ridge focuses on the development of procedures for measuring the rates of exchange of heat, moisture, momentum, trace gases, and particles using tower instrumentation, the improvement of understanding of the processes involved, and the extension of these methods to aircraft and other mobile platforms. The systems developed at Oak Ridge are the basis for the international FLUXNET program (and its North American "AmeriFlux" progeny) and the growing international light aircraft research program, focusing on CO_2 and water exchange. Oak Ridge systems supply the NWS with routine air-surface exchange data for checking the performance of operational weather forecasting models. This group has been a long-time leader of dry deposition research; AIRMoN-dry is led by ARL Oak Ridge.

ARL, Idaho Falls operates air-surface exchange stations at the Idaho National Energy and Environment Laboratory, and is a central player in studies of exchange between the atmosphere and coastal waters using light aircraft (to obtain the necessary spatial averaging). Recently, the ARL systems developed at Idaho Falls have been deployed to study air-surface exchange processes in hurricanes. The NOAA P-3 aircraft are now being equipped with ARL systems to study fluxes well above the surface. One P-3 aircraft recently completed an extensive field study during Hurricane Charley, using this new capability.

ARL, Boulder, serves as the main group in the USA studying the air-surface radiation environment and the factors that affect it. The SURFRAD and ISIS programs are providers of basic data for both weather and climate programs of NOAA. UV components of these programs also interface with NOAA's ecological programs (especially work related to coral reefs).

The **ARL Las Vegas** group maintains air-surface exchange instrumentation at ARL's Desert Rock research location on the Nevada Test Site.

ARL, Research Triangle Park has focused on pollution emissions and deposition. Emissions of dust from deserts, emissions of trace gases from biological ecosystems, and industrial emission rates are all RTP specialties. RTP scientists have conducted many intensive studies of air-surface exchange over landscapes representative of regions of the USA, leading to refined descriptions of exchange processes in the mesoscale models now commonly in use.

History

The measurement of air-surface exchange goes back to work in England in the 1930s, when Scrase first demonstrated that eddy fluxes could indeed be computed. This English interest grew during the 1940s, generating a large community of experts who developed a variety of methods to quantify air surface exchange rates without needing to perform the extensive computations involved in eddy flux evaluation.

In the early 1950s, droughts in the USSR and Australia caused a resurgence of interest in the computation of air-surface exchange rates. The goal was to understand what controlled evaporation rates and how these could be modified so as to save scarce water resources. In the late 1960s, the USA entered the race, with a burst of effort making use of the new solid-state digital computers.

In the early 1970s, there was a growing awareness that accurate weather forecasting models would eventually require accurate descriptions of air-surface exchange rates of heat, moisture and momentum. At that time, most understanding related to grassland, but much of the eastern USA is forested. NOAA/ARL generated a program to investigate how air-surface exchange could be assessed routinely over forests. This program started in Oak Ridge, as a peripheral to the dispersion studies that then dominated studies in Oak Ridge. (It was recognized that the same turbulence controlled air surface exchange and dispersion near the surface. To this day, the two specialties are strongly coupled.)

In 1981, ATDD (Oak Ridge) developed the first portable microcomputer eddy correlation system, copies of which were quickly deployed at a number of sites. As the program on dry deposition grew, “core” sites became the focus of much of the eddy correlation work – Oak Ridge, Bondville, and State College. The personnel involved in these early studies constitute the foundation of much of the work that is under way today.

Humidity and carbon dioxide

In the early 1980s, ultraviolet methods for measuring water vapor in air were common. However, work conducted a decade earlier had indicated that infrared methods would be better, if suitable sensors were available. Such sensors became available in the mid 1980s. The technical development team at Oak Ridge was then given a challenge – develop a sensor suitable for routine eddy correlation measurement of water vapor, carbon dioxide, and methane. The first two proved feasible. To this day, the methane problem has not been solved, although some recent progress has been made by the Oak Ridge group, working in collaboration with private industry partners.

ATDD soon became the provider of open-path infrared sensors for the leading eddy flux research groups around the world. Efforts to patent the developments failed, because of the widespread interest and rapid spread of the devices. Today, copies of the ARL development are in use in almost every eddy flux installation. Evolved versions are now available from a number of commercial sources.

Realization that it was now possible to monitor the exchange of carbon dioxide between the air and the land surface led to a major international meeting in 1993, organized by ARL in collaboration with Italian colleagues, at which the international FLUXNET program was started. Soon afterwards, the North American component of this larger program was started – AmeriFlux. Today, there are many AmeriFlux stations operating across North America. All make use of techniques developed by ARL. A subset of these stations is operated by ARL. This subset is a part of the ARL Atmospheric Coordinated Observation and Research Network (ACORN), and provides the surface flux data relied on by the NWS for diagnostic evaluation of its weather forecasting models. ARL air-surface exchange data are used routinely by NCEP.

Computation

A key breakthrough came with the demonstration of running-mean removal techniques as a shortcut permitting real-time evaluation of fluxes. Again, this work was completed at Oak Ridge. All known eddy correlation systems now available from commercial sources make use of this ATDD development.

Aircraft and complex terrain

A standard criticism of eddy correlation approaches is that they provide answers only representative of a small area surrounding the measurement location. Making measurements at a greater height (so as to expand the "footprint) does not work, because fluxes are not constant with height except in the lower 7% of the planetary boundary layer. (Systems erected at any height will provide answers, but these will not be indicative of surface behavior unless the measurements are made very close to the surface. Measurements made above the surface boundary layer might well be useful, but for purposes other than studies of air-surface exchange.)

To address this issue, in the mid 1980s ARL actively started developing aircraft systems that could be used at low altitudes. The Long-EZ operated by the late Tim Crawford was used as a test and development platform. A NOAA Twin Otter was selected as a mainstream operational platform.

The methodologies developed by ARL are now standard within the global aircraft eddy flux community. There is only one aircraft system available commercially – the Italian Sky Arrow. All Sky Arrows carry eddy correlation systems developed and constructed by ARL.

A series of studies of areal air-surface exchange has been conducted, using the NOAA Twin Otter, leading to a greatly improved understanding of the spatial averaging issue. In particular, these studies have shown, with great clarity, that the consequences of terrain complexity are much greater for trace gases and particles than for heat and moisture, since the fluxes of the latter pair are limited by the amount of solar energy available.

Trace gases and particles

ARL is a world leader in the direct measurement and simulation of both deposition and emission. A variety of micrometeorological methods has been used, ranging from the interpretation of gradients to direct flux measurement through eddy correlation. In recent years, significant methodology advances have been accomplished with the refinement of relaxed eddy accumulation (REA). REA permits application of direct flux measurement to a variety of chemical exchanges – from sulfur to mercury. It is the total exchange that is measured – not just deposition or emission, Hence, for the first time we have the opportunity to study the rate at which trace chemicals and particles enter and leave the atmosphere at the surface. The methodology is limited, however. Current research is attempting to make the technology appropriate for wider application.

In the last year, REA measurements of particle deposition to a maize canopy have supported results previously disregarded by many modelers because the deposition velocities appeared too high. It seems that there needs to be a major re-think.

Emission studies are concentrated at Research Triangle Park, where the major national effort on particle resuspension and trace gas emission from vegetation is centered. This is paralleled by studies of industrial and other emission inventories. All of these constitute a major item in the context of air quality forecasting.

Dry deposition monitoring

The ARL efforts regarding dry deposition were initially intended to provide a few "CORE" sites where direct measurements would be made to support the "inferential" measurements made in routine network operations. The slow initiation of inferential stations caused the ARL program to install some of these as well, although this was not the initial intent. It was thought that the EPA program, then in its developmental stages, would adopt similar sampling methodology to the ARL program. However, this was not the case. The EPA program elected to concentrate first on the validity of nitric acid vapor measurements, whereas the NOAA/ARL program consciously elected to focus first on sulfur compounds. In anticipation of an eventual comparison, the ARL inferential sites were maintained for a considerable time. They are currently being terminated, and the CORE site program is being revisited. Recent interaction with EPA is expected to result in new CORE sites, as a collaborative venture between CASTNet and AIRMoN.

There is considerable interaction with other methodologies for quantifying dry deposition, especially throughfall and calibrated watershed methods. It is anticipated that the watershed now being installed by the Canaan Valley Institute in West Virginia will offer a new opportunity to bring the various approached together.

An advanced pollutant deposition reference system has been employed extensively by the dry deposition team at Research Triangle Park. On the basis of the measurements obtained, vastly improved descriptions of dry deposition processes are now include in the air quality forecasting models becoming operational.

Wet Deposition

ARL remains a leader of the national effort to monitor the deposition of air pollutants in precipitation. ARL serves as the lead of the global effort in this regard (through the Global Atmosphere Watch). On the global scale, monitoring of wet deposition serves as a straightforward way to detect changes in the aerosol content of the lower atmosphere, and to help determine the origins of pollution that might be affecting local environments. ARL leads the international effort to ensure that wet deposition and precipitation chemistry data reported by national measurement programs can be intercompared with confidence. To this end, and in collaboration with NOAA's climate programs, ARL helps sponsor the operations of the WMO's Quality Assurance Center for Aerosol and Precipitation Chemistry.

Global air chemistry monitoring involves operation of scientifically advanced "global" stations addressing background situations, and less advance "regional" stations that focus more on the lower atmosphere and on deposition from it. ARL's activity concentrates on the latter. There are large holes in the global regional air chemistry monitoring network. These holes are typically in regions where the technological challenge is limiting. Measurement of wet deposition and precipitation chemistry is seen as an informative first step to fill in these holes. In this regard, ARL has worked extensively with the East Asia Network (EANET, led by Japan) to institute high-quality deposition measurement across east Asia. Measurements are now being made in (e.g.) Mongolia, the Philippines, Indonesia, Vietnam, Laos, Cambodia, Malaysia, China, South Korea, Thailand, as well as in Japan. Through ARL's leadership, this program is now being integrated with the global effort led by the WMO.

At this time, ARL continues to operate the research and development subnetwork (AIRMoN-wet) of the National Atmospheric Deposition Program. Recent ARL papers have pointed to the profit resulting when wet deposition data are used in conjunction with surface air chemistry observations to assess trends in air quality.

Ecosystem Associations

Clearly, any study of air-surface exchange caries overtones of ecosystem research. In practice, ARL research programs are well integrated with the ecological programs of many other agencies. In this context, ARL serves as one of two NOAA signatories to the Interagency Steering Committee on Multimedia Modeling.

A long-standing research collaboration with Oak Ridge National Laboratory has resulted in a substantial joint investment in areal deposition to moderately complex terrain, starting with studies of especially selected watersheds. Comparisons among the meteorological methodologies for deposition measurement developed by ARL and the ecologically-based protocols developed by ORNL have proved that deposition is indeed being well measured. At this time, a new watershed focus is starting, on land recently procured by the Canaan Valley Institute in West Virginia.

ARL ecosystem associations concentrate on issues related to nutrients and mercury bioaccumulation. The collaborative organizations include NMFS and NOS, Sea Grant, the NOAA Chesapeake Bay Program, the NOAA Ecosystem Research Program, and the National Atmospheric Deposition Program.

ARL Core Program – 4. Climate and Climate Variability

Overview

Until 1990, ARL had a major program addressing climate monitoring, diagnostics, and variability, involving the ARL groups in Boulder, Silver Spring, Oak Ridge, and Research Triangle Park. The measurement component of this program was concentrated in Boulder (although with some additional minor contributions elsewhere). Data analysis and interpretation was primarily at the ARL locations outside Boulder.

In 1990, the Boulder component of this program was separated from the rest of ARL. This created a monitoring program in Boulder with little immediate data analysis capability, and left several climate variability analysis and measurement projects within ARL, but unattached to the new Climate Monitoring and Diagnostics Laboratory. The skills required to analyze and interpret climate data are much the same as those required for interpretation of dispersion information, and the data systems generated to address questions of dispersion are much the same as those in place to answer questions of climate. The climate measurement and variability theme has therefore continued in ARL, and is now a major component of ARL activity.

> The ARL climate and climate variability work has been in close collaboration with NESDIS and NWS. It is presently planned to collocate the Silver Spring activity with the NWS/NCEP group as soon as it can be arranged. The work is in direct support of the NOAA goal to "understand climate variability and climate change."

The ARL Groups

Five ARL groups are heavily involved in climate and climate variability research and model development.

ARL, Silver Spring leads national efforts to derive climate trend data (temperature and ozone, primarily) from measurements by radiosondes and satellites, for the stratosphere and upper troposphere. ARL has developed a multi-media climate model, built upon the WRF system.

ARL, Oak Ridge focuses on measurement technologies and on formulating the surface energy budget on a spatial basis. NOAA's U.S. Climate Reference Network is being designed, installed and operated by ARL, in collaboration with the NESDIS/NCDC group in Asheville, NC, and NESDIS/OSD in Suitland, MD. In addition, ARL has installed a number of water vapor and carbon dioxide flux stations as a contribution to the GEWEX program of NOAA/OGP, and is actively developing improved airborne systems for extrapolating from local measurements to spatial averages..

ARL, Boulder, operates the national surface radiation network that underpins all climate-related monitoring activities in the USA and provides the NIST-based calibration of all U.S. UV monitoring networks. The Boulder contribution serves as a component of the higher-level ARL integrated monitoring program that combines routine measurement with ongoing and real-time analysis across the USA. This is the ARL Atmospheric Coordinated Observations and Research Network (ACORN).

ARL, Las Vegas is the host of the CRN activity in the desert west (at Desert Rock, NV). The intent of work at Las Vegas is to relate changes in the climate of Las Vegas to that of the surrounding desert, as a basis for refining plans for additional expansion of the urban area and for the similar growth of other areas in the desert southwest..

ARL, Research Triangle Park is leading research to explore linkages between climate change and air quality, with active collaboration with EPA and NASA.

Some History

ARL expertise in measurement technology generated the global climate monitoring program that is now CMDL, as well as a number of parallel activities that remained within the extra-Boulder ARL divisions after CMDL was formed. Much of this expertise resulted from initial work on dispersion, and on the dispersion of trace gases in the atmosphere. The work was not centered in any single location. Then, as now, the program was distributed across the various ARL locations. Today, the measurement technology expertise of ARL is actively associated with ongoing climate research in Silver Spring, Boulder, and Oak Ridge. In Research Triangle Park, the emphasis is on the linkages between air quality and climate change.

International Aspects

ARL provides the NOAA network of radiation stations satisfying the requirements of the Baseline Surface Radiation Network of the WMO. The ARL stations are significantly more sophisticated, however, since many add other aspects of the ARL "ACORN" program.

ARL's efforts to resolve disagreements between results on atmospheric temperature rends derived from radiosondes and from satellites have received international attention. ARL scientists are leaders in the international research effort to resolve related areas of uncertainty.

The Climate Reference Network is currently receiving considerable international attention. The ARL systems are likely to be replicated in the Canadian system presently being designed. Other nations are watching.

Urban Climates

There is a growing ARL focus on Las Vegas, where there is an urgent need to understand the reasons for local ozone exceedances and changes in the local climate. The situation in the desert southwest is complicated by the depth of the planetary boundary layer – typically several times the PBL depth characteristic of eastern states. The Las Vegas study will build upon the existence of the ARL mesonet in southern Nevada, which will be extended into the Las Vegas urban area.

Climate and Air Quality

The Research Triangle Park group is actively involved in adapting their CMAQ model for use in climate applications, so as to assess the changes in air quality that might be expected following a climate shift. The capability now being developed will also assess the magnitude of changes in local climate due to changes in air quality. The issue needs to be addressed from both directions.

Scientists at Silver Spring are leading a multi-agency effort to extend the Weather Research and Forecasting (chemistry) model for use in climate considerations. This extension of WRF-chem is intended to permit further extension into a multi-media context.

The ARL Atmospheric Coordinated Observations and Research Network (ACORN) is the consolidation of a number of ARL research monitoring activities, designed to combine air quality and climate aspects of the atmospheric environment across the continental USA. The SURFRAD program serves as the foundation, with total energy balance and carbon dioxide exchange sites collocated as much as is possible and with AIRMoN sites also shared as much as has proved feasible. The benefit of this collocation is substantial – for example, SURFRAD permits evaluation of the loading of particles in the atmosphere, AIRMoN-dry sites report particle concentrations in the surface boundary layer, and AIRMoN-wet measures the rate at which precipitation removes these particles from the atmosphere. As work progresses, the intent is to refine understanding of the processes that control particle concentrations in the atmosphere, for use in models linking air quality and climate.

Aerosols and Radiation

ARL has been one of the global leaders in the development of methods for deriving aerosol optical depth data from radiation measurements. In the late 1980s, ARL led the international effort to rethink the related activities of the Global Atmosphere Watch, and has since contributed strongly to the development of better methods for operational use. Today, ARL's research is tightly focused on the determination of atmospheric particle loadings and the chemistry of the particles, and on the sources, sinks, and transport mechanisms that determine these concentrations. The work involves several ARL groups (Silver Spring, Oak Ridge, Research Triangle Park, and Boulder).

The SURFRAD network is specifically designed to yield aerosol optical depth data, which are currently used to "calibrate" satellite systems. The outputs of these satellite systems (NESDIS) are then used by ARL modelers to help produce accurate forecasts of the dispersion of particles in the atmosphere, mainly of forest fire smoke and volcanic ash. These models are rapidly moving towards operationalization. Hence, the ARL program is indeed "end-to-end," with research underpinning the program and with transfer to operations of the results of the research built in. The work crosses over the NOAA mission goals. This work contributes to the ARL Weather and Water, Ecosystem, and Homeland Security programs as well as to the Climate work.

A long-standing research specialty of ARL airborne particle research concerns particle resuspension. This work has led to the development of models that forecast the onset of dust storms, as well as the dispersion of the dust clouds that are generated. The results of this work are widely used, such as in models used to assess the danger of using radioactivity to power space missions.

The air quality/climate program under way at Research Triangle Park (see above) is specifically intended to address the atmospheric aerosol/radiation/climate issue.

Climate trends and variability

Several decades ago, it was recognized by ARL scientists that radiosonde data would eventually become a critical asset in the documentation of climate change. It was also recognize that the global radiosonde network is affected by data quality concerns. For this reason, a network of high quality stations was identified, and this has been the basis for much of the current understanding of changes in upper-atmosphere temperatures (and, to a smaller extent, humidity). Recently, the data series generated by this program has become a central factor in consideration of a new satellite temperature trend products, based on microwave sounding unit (MSU) observations.

Most radiosonde data records are affected adversely by step-function changes associated with changes in instrumentation or reporting procedures. ARL analyses have addressed these issues directly, and have resulted in the development (and widespread acceptance) of procedures to reduce the consequences of such changes. At the present time, ARL is a leader of debate about how ongoing radiosonde programs can be protected from step functions in their output data, such as might be due to changes in instrumentation.

The methodologies developed by ARL to extract meaningful trends information from radiosonde data are also applied to ozonesonde data.

The role of natural variability in climate is a recognized focus of ARL research. Linkages between climate indicators and the North Atlantic Oscillation (for example) are being explored.

Water, nitrogen species, and carbon dioxide sequestration

There is no longer any doubt. These three issues are strongly interconnected, despite the fact that they are addressed separately by NOAA scientific management. ARL scientists are applying their air quality and air-surface exchange skills to explore the nature of the interdependence. A key component of this work is the operation of a small number of sites, set up under the NOAA GEWEX program of OGP, where water and carbon dioxide exchange rates are measured routinely. Nitrogen considerations are now being added to the effort. The data obtained have already demonstrated, with surprising clarity, the critical role of water availability in controlling areal CO_2 uptake by surface vegetation. In essence, CO_2 sequestration in years of drought is far less than in years of water abundance.

The current understanding has evolved from observations using ARL measurement systems at a number of sites in the US “AmeriFlux” program. Today, there is a strong need to extend this understanding to spatial domains that are not yet addressed – i.e. to areas of heterogeneous surface vegetation and complex terrain. To this end, the ARL aircraft measurement program is being redirected to focus on the need for areal averages of air-surface exchange rates of water, carbon dioxide, and nitrogen species.